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WATERLOGGING- INDUCED CHANGES IN WHEAT: BIOCHEMICAL AND PHYSIOLOGICAL INSIGHTS

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ABSTRACT

In wheat, waterlogging has a major impact on production parameters and yield. The purpose of this study was to evaluate the effects of waterlogging on wheat yield components, proline and protein content, and levels of chlorophyll b and a. Waterlogging can be caused by severe precipitation, flooding, or field drainage of a crop. Flooding occurrences are expected to become more frequent, intense, and unpredictable as a result of climate change. Each year, 10–15 million acres of wheat are impacted by this stress, which causes a 20–50% reduction in production. Given that this crop provides almost 20% of the world's daily needs for calories and protein, it is critical to comprehend how soil & plant physiological processes differ under settings with plenty of water. This will help to significantly support population food demands. We'll discuss how changes in wet soil's the pH level, redox potential, conductivity of electricity, and nutrient availability impact plants' primary responses, including root structure and growth. Waterlogging, grain for each spikes, sing-spike production, whole biomass of plants, post a thesis biomass, the leaf area at maturity were all more affected by the cultivar release year; spike for each 2 meter, 1000-grain weight, and harvest index were not significantly affected by cultivar release year. Together with the total value of photosynthetic in the top leaf, the yield of kernels and individual spikes demonstrated a significant and positive association via the leaf area at the ripening stage.

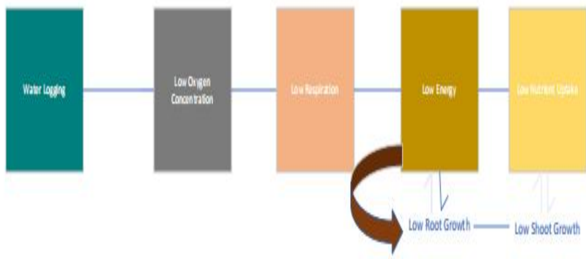
INTRODUCTION

Wheat (*Triticum aestivum*) is among the most important field crops in the world and is an annual grass of the Poaceae (Gramineae) family. Unlike the other kinds of cereal grains, wheat has special gluten proteins that enable it to create the completely viscous elastic dough needed to make noodles, pasta, and baked goods that leaven, particularly bread (Olabanji *et al*., 2004). Furthermore, wheat and its derivatives such as flour, starch, and wheat malt are frequently employed as complementary in the brewing sector. In addition, wheat supplies the human diet with vital amino acids, vitamins, minerals, healthy phytochemicals, and dietary fiber components, especially when whole-grain products are ingested. The world's most widely grown cereal crop wheat (Triticum aestivum) covers roughly 237 million hectares annually and produces 420 million tons or at least 25% of the calories are consumed by human beings (Ohiagu *et al*., 1987).

Nearly 545 million acres, or 220.7 million hectares, of land are used to growing wheat, in excess of any other major crop in 2021. Wheat is traded more globally than every other crop combined. With 771 millions of tones (850 million shorter tones) produced globally in 2021, wheat ranked second in terms of cereal output, after maize (referred to as maize in the US and Australia, but commonly called wheat in other countries). The output in wheat and other grain-based crops has quadrupled globally since 1960, and this growth is predicted to continue until the middle of the twenty-first century. The food industry's increased usage of gluten is driving up global wheat consumption (Singh *et al.,* 2023).

One important source of carbs is wheat. With a protein concentration of around 13%, which is very high related to other primary grains but relatively poor in quality (supplying essential amino acids), it is the greatest source of proteins from plants for human meals worldwide. Wheat provides a variety of minerals and dietary fiber when consumed whole. A small fraction of the general population may have dermatitis herpetiformis, non-coeliac sensitivity to gluten, coeliac disease, and gluten ataxia due to gluten, which constitutes the bulk of wheat's protein (Wu J et al., 2014).

Soil that has been saturated with water is called waterlogged soil. When soil is almost always substantially saturated with water, limiting its air phase and creating anaerobic conditions, the soil is said to be waterlogged. Anaerobiosis sets in, mesophyte roots suffer, and subsurface reducing atmosphere triggers processes including denitrification, methanogenesis, and a decrease of iron and manganese oxides in severe situations of protracted waterlogging. All plants, including crops, need air more specifically, oxygen to breathe, produce energy, and maintain their cell viability. In crops, waterlogging of the soil usually prevents air from reaching the roots; as a result, most crops, including rice (Oryza sativa), are highly resistant in waterlogging. Plant cells adapt to waterlogging-induced lack of oxygen by the formation of aerenchyma, the induction of anaerobic metabolism, and modifications to the architecture of their root systems. Because wet soils prevent the salts brought by irrigation water from leaching, waterlogging and soil salinity are frequently associated in irrigated agricultural land. Waterlogging, as far as gardening is concerned, is the process by which the soil becomes so hard that neither water nor air can penetrate 2.2%, compared to the current rate of growth of roughly 1.0% (Jackson and Colmer, 2005).



Water-logging is one of the main abiotic problems that plants face. Water-logging-induced suppression of aerobic respiration affects several developmental processes, such as seed germination, vegetative growth, and eventually, growth during reproduction. Moreover, it lowers energy metabolism. Plants adapt their morphological structure, energy metabolism, signaling processes, and internal hormone synthesis to the stress of waterlogging. It is well recognized for water from soil logging poses a serious abiotic risk and that the restrictions it imposes on roots have a discernible effect on plant growth and development. If that they take place in the spring, they can greatly reduce seed germination and the development of seedlings. Thus, soil water-logging is important for the growth, survival, and development of plant species not only in natural settings but also in agricultural and horticultural systems (Dat *et al.,* 2006).

Soil water logging causes quick changes in soil characteristics. Anaerobic conditions arise when water fills the soil pores, dislodging gases and decreasing gas transport. This leads to the accumulation of phytotoxic chemicals. All of these modifications have a significant influence on the capacity of plants to endure these circumstances. There is a decrease in photosynthesis along with hydraulic conductivity of root, an increase in the stomata resistance, and a decrease in photo-assimilate translocation. However, a change in the biochemical & metabolic processes frequently seen when O2 access becomes restricted is one of the most thoroughly studied plant responses to hypoxia and anoxia (Dat *et al*., 2004). Under circumstances unfavorable for aerobic energy production, oxygen-independent energy-generating metabolic pathways are made possible by the selective synthesis in group of roughly 20 anaerobic stress proteins (ANPs) (Subbaiah and Sachs, 2003). Additional adapted features comprise morphological and anatomical modifications, including development of an aerenchyma, adventitious roots & hypertrophied lenticels (Folzer *et al.,* 2006).

Wheat yield is severely limited by waterlogging (Collaku and Harrison, 2002). Because of the correspondingly low soil redox potentials, roots in wet soils are exposed to both low levels of oxygen (hypoxia) and higher amounts of reducing soil chemicals (Ponnamperuma 1984). Waterlogging decreases wheat grain yield production grain quality and the accumulation and the mobilization of the carbohydrates into grains (Zhang *et al*., 2011). This is most likely because it impairs the functioning of the root systems. Numerous studies have highlighted the necessity of creating cultivars with greater resistance to the detrimental root environment of wet soil in order to boost wheat yields (Musgrave and Ding 1998, Setter and Waters 2003). If agricultural productivity is to be preserved in soils that are prone to waterlogging, roots' capacity to return to normal function following a period of hypoxic stress is also crucial. Even when the stress has subsided, exposure to waterlogging frequently has a lasting impact on root growth (Malik *et al*. 2002).

Normal growth condition for wheat

Wheat yield is severely limited by waterlogging (Collaku and Harrison, 2002). Because of the correspondingly low soil redox potentials, roots in wet soils are exposed to both low levels of oxygen (hypoxia) and higher amounts of reducing soil chemicals (Ponnamperuma 1984). Waterlogging decreases wheat grain yield production grain quality and the accumulation and the mobilization of the carbohydrates into grains (Zhang *et al*., 2011). This is most likely because it impairs the functioning of the root systems. Numerous studies have highlighted the necessity of creating cultivars with greater resistance to the detrimental root environment of wet soil in order to boost wheat yields (Musgrave and Ding 1998, Setter and Waters 2003). If agricultural productivity is to be preserved in soils that are prone to waterlogging, roots' capacity to return to normal function following a period of hypoxic stress is also crucial. Even when the stress has subsided, exposure to waterlogging frequently has a lasting impact on root growth (Malik *et al*. 2002).

Temperature variations throughout the year may have an effect on a crop's phasic growth and grain output. For optimal emergence, development, and blooming, wheat a winter cereal needs certain climatic conditions (Dabre *et al*., 1993). It also grows more venerably when exposed to extreme temperatures throughout the reproductive phases (Kalra *et al*., 2008). An early seeding result in weak plants with a weak root system, which can cause uneven germination, frequent embryo mortality, and endosperm degradation from bacterial or fungal activity (Paul, 1992). However, late planting reduces grain development, germination, and growth (Haq & Khan, 2002) and results in poor tillering because to low temperatures and winter injury (Tahir *et al*., 2009). According to (Singh and Uttam, 1999) yield loss is projected to be 39 kg ha-1 day-1 for every day that the optimal sowing timing is delayed. Regular sowing increases the number of tillers, spikes, grains spike-1, and grain weight while also extending the tillering period (Ishag, 1994). These factors ultimately increase the yields of grain and straw (Qasim *et al*., 2008). Additionally found that early sowing produced a greater grain yield compared to late sowing.

Because the relationship between the highest temperature and sowing date provides the best estimates of the growth intervals in different wheat growing areas, the local climate and related micrometeorological variations are crucial in determining the ideal date for sowings in a given location (French *et al*., 1979). Previous investigations (Kalra *et al*., 2008) have stressed the importance of examining how crops react to weather variations in order to assess the effects of seasonal temperature changes and estimate the yield dependency of crop temperature rise.

Environmental parameters influencing wheat waterlogging Reponses

Wheat is less severely affected by waterlogging in cooler weather (Luxmoore *et al.,* 1973). Reduced temperature causes slower shoot development, slower root metabolism, and slower O2 loss from the soil, which reduces the need for nutrients and water (Trought and Drew 1982). Soil anoxia may not develop in particular circumstances (such as low biologic activity, low temperature, and mass water movement through the soil) (Setter & Waters 2003). According to Cannell *et al.,* (1980), one example of how soil type affected wheat's responses to the middle of waterlogging was yield, which was decreased by 16% in clay soil as opposed to 7% in sandy soil. This difference was likely due to the clay soil's more slow return to toxic conditions after drainage and faster oxygen depletion during waterlogging and a greater denitrification for the clay, as suggested by those writers (Cannell *et al.* 1984).

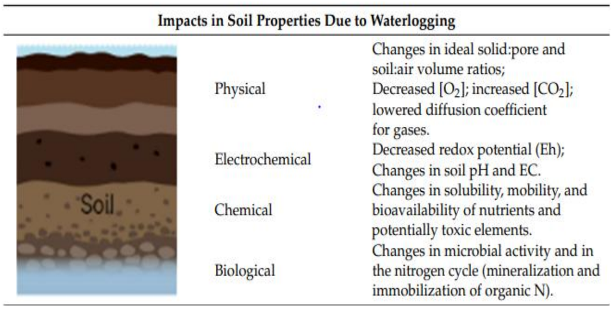
The extent of plant damage is impacted by the depth of waterlogging, such as wheat tillering was decreased by 62%, 45%, and 24% & adventitious roots main axis length per plant, 73%, 58%, and 39%, respectively, if the water surface reached 0, 10, and 20 cm below the surface (*Malik et al.,* 2001). With a toxic soil zone upward a water-saturated hypoxic soil, primary root development can also rise. For instance, with wheat plants waterlogged to a depth of 10 cm below the soil surface, seminal root dry matter (DM) rose by 50% in comparison to plants waterlogged to the soil top. Using SEW30 (the total amount of extra water that happens each day in the tip 30 cm of soil, the duration and thickness of waterlogging at certain field locations have been reported. The fact that wheat growth and yield gradually declined with the length of waterlogging (Marti *et al.,* 2015) and that repeated waterlogging episodes might have cumulative effects (; Belford *et al.,* 1985) lend support to this approach. However, because SEW30 ignores factors including temperature, flooding frequency, potential shoot submergence levels, vulnerability at various developmental phases, and varying recovery responses, its application has been criticized (Malik *et al.,* 2001).

While the main factor causing wheat root growth reduction is low O_2 stress (Trought and Drew 1980), higher density in Fe^{2+}, Mn^{2+}, ethylene, CO2, and organic acids are also caused by waterlogging and can be harmful to roots (Ponnamperuma, 1984). Fe^{2+} and

Mn^{2+}, two soluble metal ions, have the potential to grow to hazardous concentrations (Setter *et al.,* 2009). Root cell pH may drop due to high CO_2 concentrations (Greenway *et al.,* 2006), and root elongation may be inhibited by high ethylene concentrations (Huang *et al.,* 1997). Although there are little data on how organic acids affect wheat, they have been shown to have varying negative impacts on K+ fluxes in the roots of two different kinds of barley (Hordeum vulgare), particularly in terms of size (Pang *et al.,* 2007), hence wheat should also studied in this regard.

Main waterlogging effect in soil

When soil moisture levels exceed the field's capacity, waterlogging may result. Under such conditions, more water becomes saturated the soil pores whether or not there is a surface of water on the soil outer layer. Most terrestrial plants are negatively influenced by this abiotic stress, which reduces agricultural output. Reduced root biomass can lead to changes in the electrochemical, chemical, in nature, physical, & soils biological properties, which can hinder vegetative development & cause plant organ senescence. Because majority of the pores in a damp soil are filled with water, the ideal ratios of solid to pore material (50:50) and soil to air volumes (75:25) are changed. This has an impact on the physiological performance of the plant. The oxygen substance of the soil should be at least 10%, but the atmosphere has 21% of it. In places with waterlogged soil, the dissolved oxygen content is less than 0.05 mmol m^{-3}, while it is around 0.23 mol m^{-3} in fertilized soil. Because roots and microbes respire aerobically, the soil environment is normally rich in CO_2 & lacking in O_2. On the other hand, quick O_2 intake & CO_2 emission made possible by excellent aeration provide plants with enough oxygen to satisfy their nutritional needs and to grow.



Impacts in soil properties due to waterlogging

Since the diffusion of gases in water is nearly 104 times less than in air, exchanges of gases within soil and atmosphere almost cease when waterlogging is established. Inadequate O_2 levels and hazardous CO_2 concentrations in the soil are caused by ant roots microbial activity and respiration which utilize the oxygen held in the soil and create an anoxic/hypoxic environment in the rhizosphere. Soil waterlogging can lead to notable alterations in redox potential (Eh). The most crucial physicochemical factor in determining a flooded soil's degree of oxidation is it's eh value. Soil $[O_2]$ often has an inverse relationship with the Eh. Nitrogen (N), which is essential elements that limits production and is necessary for plant growth, is usually taken up from the soil as nitrate (NO_3^-) or ammonium NH4+ (NH_4^+). The type of nitrogen in the soil can affect several physiologically and metabolically processes in plants, including nutrient intake, the activity of enzymes respiration and photosynthesis rate, balance of water. In addition to its quantity. Significantly reducing gas diffusion due to waterlogging causes an increase in NH4+ of the soil. This ion is involved in many metabolic processes, but if it is the only supply of N, it may also strongly impede the absorption of K, an important nutrient which also plays a part in various biological processes in plants.

Effect of water availability on wheat growth

The most critical physiological factor affecting the amount and quality of grain yield performance in crops is the availability of water. The impact of availability of water has been investigated in a 12-year experiment period of winter wheat agronomic experiments conducted at the Nagygombos research site (Hungary). The experimental site's annual precipitation falls within the 550–600 mm belt that borders the northern limits of Great Hungarian Plain, and the mean depth of ground water varies between 2 and 3 meters. The location reflects the usual average lowland characteristics of the nation.

Crop yield both quantity and quality have been affected differently by crop years with diverse patterns of precipitation. Overall, there was a favorable association between yield data and annual precipitation. The presence of water affected quality manifestation in a variety of ways. Hagberg values were impacted by better water availability, which has frequently led to lower grain quality, particularly in wet gluten. While the overall output was lower due to the drought, in certain crop years it improved the quality of the product (De San Celedonio *et al*., 2014).

Impact of waterlogging on Wheat growth

One of the primary abiotic factors influencing agricultural productivity globally is waterlogging. However, because of increasingly intense and erratic rainfall brought on by climate change, there have been more flooding incidents in recent decades. Ten to fifteen million hectares of wheat are grown, and overall waterlogging damages them, resulting in 20 to 50% yearly production losses. Extreme weather events will probably increase due to global warming, increasing the possibility of flooding in new locations. Water is essential for plant growth and for the way that plants interact with their surroundings. On the other hand, too much water in the soil can alter its characteristics, reducing the amount of available oxygen and preventing it from diffusing to plant tissues creating an environment that is either hypoxic or anoxic. Weather patterns and the extent and length of waterlogging throughout the crop's developing stage are two factors that affect the consequences of waterlogging. A lack of oxygen in a soggy environment can stunt root growth and eventually cause root death. Under such conditions, energy-dependent processes like the uptake and transfer of nutrients and water to the shoot are hindered, putting the plant's growth and development as well as its final production at risk (Henshaw *et al.,* 2007).

Furthermore, there may be declines in the amount of nitrogen in the leaf, as well as in the leaf's water potential as well as in stomatal conductance, rate of CO2 assimilation, photosynthesis, and chlorosis and senescence. In water-logging sensitive plants, down-regulation of photosynthetic machinery may leads to an excessive formation of reactive oxygen species (ROS), which disrupts normal metabolism and causes severe oxidative damage and cellular structure deterioration. ROS induce lipoperoxidation processes, which damage nucleic acids, cause membrane damage, degrade proteins, inactivate enzymes, and ultimately cause cell death. Roughly 20% of the world's protein and energy needs are met by wheat, the third most widely grown cereal crop.

Global wheat output is achieved by productivity of about 3.5 t ha^{-1} in 2020. Increasing wheat yield and ensuring production stability are crucial for ensure food security, especially light of projected population expansion and climate change scenarios. We will discuss a few topics associated with the consequences of waterlogging on wheat crops, including the effects on the root system and plant development, as well as, nutrient availability, pH, soil redox potential & electrical conductivity. Major leaf responses to oxidative stress that are connected to the activity of photosynthesis and membrane integrity will also be our main emphasis (Dickin and Wright, 2008).

Wheat Crop Responses to Waterlogging

Global wheat output is achieved by productivity of about 3.5 t ha^{-1} in 2020. Increasing wheat yield and ensuring production stability are crucial for ensuring food security, especially in light of projected population expansion and climate change scenarios. We will discuss a few topics associated with the consequences of waterlogging on wheat crops, including the effects on the root system and plant development, as well as, nutrient availability, pH, The way that plants react to waterlogging depends on a lot of variables, including the duration and depth of exposure as well as stage at which the plant is developing. Reproductive phases of wheat includes stem extension stage leading upto and following an thesis have been noted by multiple writers as the times when the plants are particularly vulnerable to the effects of waterlogging stress. whereas (Pampana *et al.*, 2009) discovering no difference at any 3 & 4 leaf stages, Wu et al. has reported the adverse effect at the seedling stage.

According to Ding et al., waterlogging during the seedling, jointing, & tillering stages reduced wheat production by 9 to 15%, and at the thesis and milk-ripe stages, it reduced the area of leaves by 10% and 29%, respectively. Crop damage is significantly impacted by the length of waterlogging incidents. In general, the adverse impacts on plants increase with duration. Waterlogging has been linked to reported effects on plant respiration, transpiration, antioxidative system, and photosynthesis. In addition, it has been connected to lower accumulation and remobilization in photosynthetic products, as well as increased organ senescence. These factors eventually result in a drop in yield components such spike quantity, grains per spikes, and kernel weight. Although the main cause of the reported negative impacts is lower soil O2 availability, plant morphological, physiological, or anatomical alterations may aid to lessen the effects of such a deficiency (Herzog *et al.*, 2016).

Root

In order to absorb water and nutrients, store photo assimilates, provide anchoring, mechanical support, and connect with the rhizosphere, roots are vital organs. Roots need energy via cellular respiration to do this. The plant is largely affected by waterlogging conditions at the root level, and the first reactions take place. Shoot development is severely impeded by root injury. Root death and stunted development greatly reduce the dry bulk of seminal roots. Low (O2) levels in the rhizosphere during waterlogging increases anaerobic respiration, which reduces ATP generation. A severe loss at root hydraulic conductivity results in impaired phosphorylation of aquaporins, which controls cell water flow and compromises water and nutrient absorption. Furthermore, the decrease in soil Eh might make Mn2+ and Fe2+ more readily available to harmful concentrations, leading to their build-up in the roots. Saturated soils may see an increase in organic acid levels and other potentially harmful metabolites that are created when organic matter breaks down in anoxic soils (Fagerstedt *et al.*, 2020).

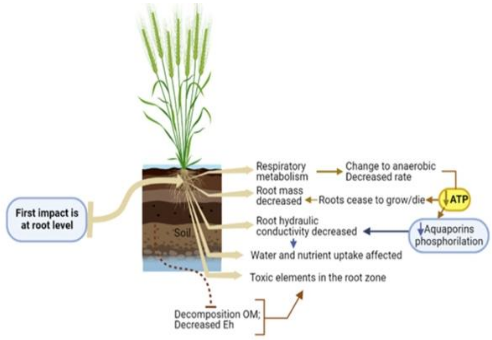


Figure 1. Major effects of waterlogging occurring at root level. Figure elements created using biorender.com (accessed on 15 December 2022).

In addition to producing reactive oxygen species (ROS), including hydrogen peroxide, that can harm cells, anaerobic respiration can lead to the buildup , acids such as lactic acid, ethanol, and aldehydes, among other substances. Toxic levels of organic acids in rice can lead to root occlusions, decrease nutrient absorption, increase outer cell wall suberization and lignification, and hinder root respiration. Organic acids have been shown to have negative effects on K+ flux in the roots of barley. Additionally detrimental to roots are endogenously generated CO_2 and ethylene, which can cause the pH in root cells to become more acidic and prevent root expansion when high in ethylene. Certain plants that can withstand low oxygen levels (hypoxia) or no oxygen levels (anoxia) might change morphologically to make up for the oxygen deficiency in their root zone (Huang *et al.*, 1995).

A typical reaction to waterlogging is adventitious root production from stems or branches, which greatly increases plant life and productivity by promoting gas movement and nutrient and water intake. O_2 may be taken up and transported by these roots, allowing roots to be submerged in it. According to Wiengweera and Green way, adventitious roots acquired K and P more efficiently than tap roots in wheat plants affected to waterlogging. Different wheat genotypes can also have different root architectures, which can lead to different root dispersion in the soil. A thinner rooted system may be more suited for intake of oxygen in flooded situations since upper soil layers frequently contain greater amounts of oxygen then deeper ones (Gibbs et al., 2003).

A build-up of ethylene under waterlogging stress can also trigger the planned death of root cortex cells, causing adventitious roots to form an aerenchyma. Wheat aerenchyma growth enhances energy availability and decreases hypoxic stress, which can improve the tolerance of plants and survival in waterlogging and oxygen-deprivation environments. Large, linked, gas-filled intercellular gaps in this specialized parenchyma tissue create a low-resistance channel that improves gas transport throughout the roots and shoot. Moreover, hazardous volatile chemicals like CO_2 can be released from buried tissues by aerenchyma. However, adventitious root development is insufficient to completely offset seminal root loss, and the internal O_2 transport to the apex that permits root extension is restricted (van Bodegom *et al*., 2013).

Shoot Development and Productivity

Plants may develop because of their roots' ability to absorb water and their leaves' ability to transpire. However, when plants are exposed to waterlogging, some genotypes may exhibit substantial deficits in certain important metabolic processes, including respiration, photosynthesis & transpiration. The negative impact on processes result in the severe lack of energy, stunted development, and increased senescence of the leaves and other organs, which lowers grain production by preventing the accumulation & remobilization of photo, assimilates. According to a number of writers, waterlogging severely stunts the growth of the plants' aerial components. This is mostly because it slows down the pace at which leaves elongate, which leads to smaller leaves (Malik *et al*., 2002).

However, it also reduces the number of cultivators and impairs their development. In contrast to well-drained plants throughout period report that when 3-week-old plants were subjected to 3 to 21 days of waterlogging, and after recovering for 21/7 days, the shot mass dropped via 43% to 72%. It states that Herzog et al. wheat plants cultivated in wet soil saw a 67% decrease within average shoot dry weight. This decrease severely diminishes the area accessible for absorbing light and restricts photo assimilation, along with the plant's general wilting and basal leaf senescence. According to Goud et al. (2022), chlorosis causes a rise in bread wheat mass of 8 to 21% in waterlogged plants and 33 to 70% to plants that had been submerged in water for 14 days.

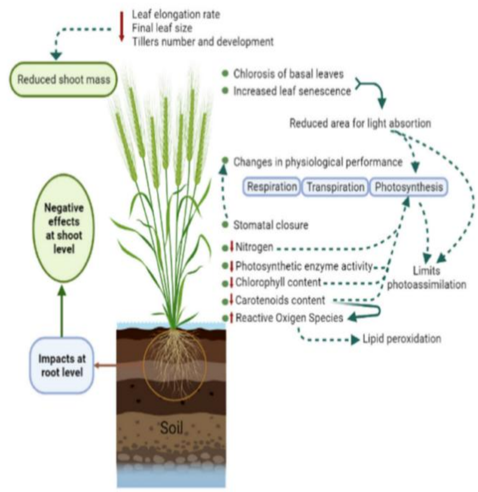


Figure 2. Effects of waterlogging at shoot level. Figure elements created using biorender.com (accessed on 15 December 2022).

Physiological responses of wheat to Waterlogging

Gas exchanges and sugar Metabolism

The great ability of the photosynthetic process to adverse conditions results in changes in both photosynthesis and respiration (Pn) which are commonly employed as markers of productivity under stress. While plants that are tolerant of waterlogging show less severe effects as well as a change in the responsiveness of some parameters, vulnerable plants exhibit substantially decreased physiological activity, which may lead to cell death. Wheat plants exposed to waterlogging may have a decrease in shoots physiological performance due to compromised root function. Common reactions to this stressful environment include stomatal closure, decreased transpiration, and suppression of photosynthesis. One of the main parameters affecting photosynthesis is stomatal conductance (gs), which has a major impact on photosynthetic rates in wet environments. Reduced (gs) and stomatal closure provide a reduction in leaf transpiration. But this also results in a decrease in the internal level of CO2 (Ci), which restricts the fixation of carbon, decreasing photosynthesis and raising respiration, all of which have a detrimental effect on plant productivity (Scotti-Campos *et al*., 2014).

However, non-stomatal mechanisms like reduced chlorophyll production and degradation can also cause photosynthetic rates to drop, which can lead to leaf senescence with yellowing. Reduced photosynthetic enzyme activity, low nitrogen content, and ROS damage to the photo system II intensified the negative impacts of waterlogging and the fall in photosynthetic activity. Plants need Pn to transform water and carbon dioxide into sugars, which serve as their main energy source for many cellular processes. Pn and respiration can alter as a result of waterlogging, which might have an impact on sugar metabolism and energy balance. Lower Pn rates at the beginning of waterlogging related to accumulation of sugar in the leaves rather than stomatal closure. It has been documented that sugars can accumulate in the leaves of soggy wheat plants. When waterlogging first occurs, root hypoxia can lead to the buildup of carbohydrates because it prevents the plant's aboveground and root systems from growing quickly. In these circumstances, the leaves produce more sugar than are consumed (Wu *et al*., 2014).

Simultaneously, restrictions within the root system reduce the roots' ability to transfer phloem, which also helps the leaves accumulate photo assimilates. Because the negative feedback , carbohydrate buildup, the ensuing overproduction of sugar and decreased phloem transport capacity in hypoxic roots cause a further drop in Pn. Plants that are subjected to prolonged floods suffer from a shortage of energy and carbohydrates as a result of decreased photosynthesis & aerobic respiration. Consequently, given that the plant has to use its accumulated glucose reserves to sustain metabolic activity in anaerobic environments, the initial carbohydrate stores may play a critical role in tolerance to hypoxia and anoxia. Additionally, sugars help stabilize membrane structures maintain cell turgid via osmotic processes in plants stress responses and adaptability both osmoprotection and adaptation (Sharma *et al*., 2019).

Chlorophyll and Carotenoids

The two main functions of photosynthetic pigments, which are essential chemicals in the process of photosynthesis, are the absorption of light and the synthesis of reducing agents. Variations in the composition and concentration of pigments directly impact the rate of photosynthetic activity. The transformation of light radiation towards chemical energy depends on chlorophylls. They are exclusively linked to the effectiveness of photosynthetic processes, and consequently, to the development and environmental adaptation of plants. While chlorophyll b is the primary auxiliary absorbing light pigments in light harvesting complexes, chlorophyll is found in the reaction centers for both the photo systems (PSI and PSII). Waterlogging has been linked to drops in chlorophyll concentration, according to several writers. Four wheat genotypes saw chlorophyll decreases ranging from 15% to 33% during the emergence stage following a 10-day stress (Pan *et al*., 2021).

At the tilling stage, six wheat cultivars that had been waterlogged for 28 days showed losses ranging from 41% to 61%. Carotenoids have a number of roles in the metabolism of plants. They collect and transmit light energy towards chlorophylls via the photosynthetic process as auxiliary antenna molecules, or pigments involved in photosynthetic chemistry. Additionally, Carotenoids are crucial for oxidative stress tolerance because they scavenge reactive oxygen species (ROS) and suppress lipid per oxidation, which protects the photosynthetic machinery. Studies on plants vulnerable to wheat have shown a decrease in Carotenoids pigment concentrations due to waterlogging. Nonetheless, the quantity stayed high in genotypes that were tolerant. Overall, plants exposed to extended durations of waterlogging experience a more severe reduction in Carotenoids concentration. At the tillering stage, following 7, 14, and 21 days respectively for water-logging, the Carotenoids concentrations fall between 11–15%, 16–38%, and 29–67%. According to the same study, waterlogging for 14 days during the elongation stage resulted in more severe Carotenoids decrease (32–49%), demonstrating that the impacts vary depending on the crop growth phase (Cessna *et al*., 2010).

Chlorophyll florescence

Chlorophyll absorbs light photons in the light harvesting antennas and partially (about 2%) reemits them as fluorescence. In order to evaluate a plant's effectiveness in harvesting light, fluorescence from chlorophyll is a sensitive and dependable method that may be used in conjunction with gas exchange data. When stress is present, this parameter may drop, allowing for quantitative comparison of stress responses providing indirect insight into the photosynthetic efficiency of leaves. PSII maximal quantum efficiency (Fv/Fm) quantifies the proportion of active PSII reaction centers. Decreases in this ratio may be a sign of harm to the photosynthetic system, which might lead to a drop in Pn. There have been reports of Fv/Fm ratio reductions in wheat as a result of waterlogging, which suggests PSII degradation and, as a result, a lower use-efficiency of collected photon energy (Shao *et al*., 2013).

Oxidative stress

Despite the fact that ROS are common result of plant cell metabolism, abiotic and biotic stresses frequently interact with oxidative stress, which is characterized by an increase in intracellular ROS. Reactive oxygen species can be further classified as non-radical (singlet oxygen (1O2), hydrogen peroxide (H_2O_2), or free radical (superoxide radical (O2•), hydroxyl radical (OH•), perhydroxy radical (HO2 •). Their potent oxidizing action can induce lipoperoxidation, the breakdown of membrane lipids, oxidant damage to DNA and proteins, and serious cell injuries when it accumulates in mesophyll cells. Since carbon, carbon double bonds among lipids are preferred for reactive oxygen species (ROS), cell membranes are very vulnerable to lipoperoxidation and include a high concentration of unsaturated fatty acid (PUFA), which especially prevalent in chloroplasts. Excessive formation of reactive oxygen species (ROS) inside leaves is caused by down regulating photosynthetic machinery in plants that are sensitive to waterlogging. The early senescence of leaves due to nitrogen remobilization in younger leaves is preceded by a rapid chlorosis in of basal leaves (Baxter *et al*., 2014).

Oxidative stress is indicated by the surviving leaves' decreased chlorophyll concentration. Overwatering can significantly raise the ROS concentration compared to typical growth conditions, severely damaging plant cells through oxidative stress. This increase, which is frequently linked to higher quantities in malonyldialdehyde (MDA), one of the numerous lipid oxidation products, indicates the existence of lipoperoxidation processes. Oxidative stress resistance may be higher in genotypes with reduced MDA levels under stress. Additionally, ROS buildup seriously disturbs the ionic balance of plants, which has an immediate impact on the operation of several cation and anion channels. By activating their antioxidative defense mechanisms, Wheat plants tolerate oxidative stress using a variety of mechanisms, including enzymatic and non-enzymatic ones, to neutralize excessive ROS and reduce the degree of oxidative damage (Manik et al., 2019).

Antioxidant enzymes including catalase (CAT), superoxide dismutase (SOD), reduced glutathione (GR) & the peroxides ascorbate break cycles of uncontrolled process of oxidation by neutralizing, eliminating or scavenging ROS and its intermediate, turning ROS into innocuous substances. Ascorbic acid (AsA), reduced glutathione (GSH), Carotenoids, and tocopherols are examples of non-enzymatic antioxidants that are essential for protecting cellular components and stabilizing membranes. Waterlogging-induced increases in antioxidant enzyme activity have also been seen in resistant wheat plants, according to many investigations (Shabala *et al*., 2014).

Waterlogging effect in yield components

Wheat is sensitive to waterlogging, and under such conditions, there have been several reports of plant yield reductions in grain. Thirty days of waterlogging during seeding, the seedling's, flowering, and grain-filling resulted in a 50–70% reduction in grain output because of poor set of seeds and few spikes per unit area. Waterlogging over 21 days during the tillering stage decreased production, resulting in value decreases ranging from 37% to 60%. Reductions in the total numbers of grain per spike, numbers of spikes/plant, and the thousand-gram kernel weight were also noted in genotypes prone to waterlogging. Since the quantity of spike per unit area strongly correlates with the emissions, growth and development, & survival of tillers, these characteristics are critical as it directly affects wheat output.

Studies employing diverse genotypes of wheat exposed to waterlogging during the tillering stage revealed that reduce the quantity of released tillers did not consistently align with decrease in the quantity of fertile ones. This implies that the plant possessed a proficient tactic for sustaining production while addressing energy scarcity (Olgun et al., 2008).Fertile tillers contribute very little to the ultimate yield production, which leads to a fall in productivity while the number on fertile tillers is constant. With longer waterlogging durations (5 to 50 days), there was a considerable drop in the number of seeds per spikes (2.0 to 78.8%), with the control plants showing the maximum seed number per spikes at day 50 and the lowest value at day 50. Ding et al. (2020) found that waterlogged wheat had lower single-spike yield (9%) & lower kernels/spikelet (5%), but no changes in the spikelet fertility or spikelet's per spike were noted. Alizadeh,Vaskasi (2018) observed a similar pattern, reporting decreases in the production of kernels per spike and individual spikes in wheat plants that were wet during the tillering and elongation phases (Bailey-Serres *et al*., 2008).

Genetic Response to waterlogging

Unfavorable conditions, such as waterlogged soil, can cause a variety of morphological and physiological alterations in plants. Numerous responses to stress genes are triggered, and vital functional proteins are produced, to improve waterlogging resistance. In response to waterlogging (Wei *et al*.,2021) found that two wheat genotypes significantly down-regulated genes associated to photosynthesis and genes involved in the harvesting light chlorophyll protein complex (for example, LHCB1, LHCB3, LHCB5, LHCA1, and LHCA4) (Wang *et al*., 2022).

Tong et al. (2021) observed increased expression of Respiratory Bursts Oxidase Homolog (RBOH) in wheat, a protein that controls the build-up of reactive oxygen species. Waterlogging tolerance genes have been identified based on their involvement in the ROS production pathway, which is crucial for controlling the formation of aerenchyma in roots. The waterlogging tolerance characteristics associated with root freshly harvested biomass, shoot fresher biomass, levels of chlorophyll), & the germination index were also discovered to have several Quantitative Trait Locus . The genetically modified varieties of wheat that can withstand waterlogging can greatly benefit from understanding the genetic mechanisms associated with this stress (Borrego-Benjumea *et al*., 2020).

Morphological changes in wheat plants under waterlogged condition

Notable arable land areas worldwide are susceptible to floods or waterlogging. In regions with heavy rainfall, soil waterlogging is prevalent. Even in drought-stricken areas, low slopes, thick texture (clay) soil & poorly drained soils are additional causes of floods. When there is waterlogging, there reduces gas exchange among the air and the soil. This situation causes the soil's oxygen content to rapidly decrease; within a day, the soil can grow hypoxic (having little oxygen) or anoxic (having no oxygen) (Armstrong *et al*. 2009). Insufficient soil oxygen can affect plant nutrition availability, which can have an indirect effect on plant output, or it can directly affect root metabolism (Bailey-Serres *et al*. 2012). In order to generate energy for development via breakdown of organic components, oxygen is required. According to (Ahsan *et al*. 2007) roots and aerobic bacteria cease developing and may even die when the oxygen in the soil is reduced to nearly nothing.

The effects of waterlogging can be seen in a number of physiological processes, including the absorption of water and the relationships between root and shoot hormones (Licausi and Perata, 2009) it can also lead to nutrient deficits by reducing the absorption and transportation of ions through roots; element toxicities, including those involving Na, Fe, Mn, Al, and B (Zhang *et al*. 2011) and superoxide dismutase activities (Huang *et al*. 2015). Flooding or waterlogging inhibits the growth of shoots and roots as well as the yield. Plants' ability to withstand waterlogging is influenced by their genotype or type of variety (Mano and Oyanagi 2009) growth stage, water level depth, length of the waterlogging event, and environmental factors like temperature as well as primary aerenchyma development (Yamauchi *et al*. 2013).There is evidence of genetic variations in wheat's resistance to waterlogging. Waterlogging of wheat decreases the number of kernel per spike, photosynthesis, leaf elongation, and ultimate yield. For 20 days, waterlogging can lower winter wheat grain output by between 32 to 94%.

Leaf Senescence and Chlorosis

Plants produce dry biomass and crop yield primarily through photosynthesis. The development of high-yielding cultivar breeding has led to advancements in leaf photosynthesis. The quantity and nature of light above the surface in the green region following anthesis determines the critical assimilation moment that supplies carbon in the grain during the wheat spike growth stage. Normal ageing and other pressures cause this assimilation region to shrink. Senescence in plant is described as the age-dependent planned disintegration & degeneration process of organs, cells, as well as the entire organism, culminating in death. Senescence is thought to be the last stage of leaf formation (Jiang H *et al*., 2002). The loss of chlorophyll and the breakdown of the photosynthetic machinery, which lower the capacity and efficiency of photosynthetic energy conversion, are the two most notable aspects of leaf senescence. Furthermore, the senescing leaves' chloroplasts have a decreased volume, a spherical form, and a diminished thylakoid system. Senescence in cereals is significant because it takes place during the filling of grains, and there is data that implies earlier senescence could be yield-limiting. The rate of senescence onset and the pace at which leaves senesce over time differ between wheat genotypes. It was also shown that, in wheat, the rate of senescence was connected to the yields under drought (Hafsi M *et al*., 2000).

Management strategies for wheat crop under waterlogging stress

Concerns about waterlogging are also shared globally it affects 16% of US soils, 10% of Russian agricultural land, and irrigated crop producing regions in Bangladesh, China, India, and Pakistan. Every year, waterlogging affects 10 to 15 million hectares of wheat worldwide, resulting in output losses of twenty to fifty percent (Hossain and Uddin, 2011). Other grain crops including wheat, barley, canola seeds, field peas, lupines, and chickpeas also experience yield losses due to waterlogging (Solaiman *et al*., 2007).Effective soil & crop management techniques enhance crop yield and soil quality by decreasing the requirement for new agricultural land while also improving ecological and financial flexibility.

Enhancing soil management can decrease surface runoff, boost infiltration, and increase plants' access to water and nutrients (Amare *et al*., 2013). Managing crops can help increase yields. The effects of waterlogging on soil characteristics, plant development, and agricultural management strategies to lessen waterlogging are the main topics of this review. In order to assure soil sustainability & crop management in waterlogged circumstances, future opportunities are recommended by identifying the gaps in present knowledge, technology and farming methods.

Soil Management

Tillage, drainage, and traffic control are examples of soil management techniques that can directly or indirectly change the structure of the soil. A large number of these modifications are reversible and of a brief duration. Much more lasting changes to soil structure might result from management-induced modifications to the amount and qualities of soil. Sustainable management techniques must keep the soil's structure in an ideal condition for a variety of activities pertaining to agricultural productivity and environmental quality over the long run (Belmonte *et al*., 2018).

By regulating infiltration, surface of the soil biological communities play a crucial role in many ecosystems by ensuring that crops, soil biota, nutrient cycles, and vascular plants have access to enough water. By fixing carbon in the atmosphere (C) and nitrogen (N), they boost biodiversity, quicken the pace at which soil forms, and aid in the biogeochemical cycle of nutrients (Elbert *et al*., 2012). Therefore, focusing on the soil surface is essential when planning management strategies.

Drainage System

One of the primary methods for increasing yields per unit area available agricultural area is land drainage. Agricultural drainage's three major goals are to reduce soil submergence, regulate salinity, and open up new area for agriculture (Singh and Panda, 2012). However, when compared to irrigation, drainage an effective agricultural engineering method to prevent waterlogging has not received the same priority from individual farmers or from government organizations. Worldwide, as well as in some regions of Australia, drainage is utilized to reduce waterlogging. Drainage may successfully reduce the water table and increase agricultural yields, according to a number of researches done in England, Europe, & North America (Gramlich *et al*., 2018). Additionally, it was said to significantly lessen wheat yield losses in south-western Victoria caused by waterlogging. Even with the yield losses linked to waterlogging on texture-contrast soils in Australia that are prone to flooding, the HRZ still has a low rate of widespread drainage adoption. Mole drains, subsurface drainage, and surface drainage are some of the techniques that have been suggested to reduce the issues caused by waterlogging (Singh and Panda, 2012).

Strategic deep Tillage and subsoil manuring

A single or infrequent application of strategic deep tillage (SDT), using rotary, deep ripper, spader, moulds board plough, or disc plough, can assist maintain the no-till system's long-term production. It has been proposed that deep tillage and soil cultivation to release compacted soil layers, especially the clay subsoil, can increase subsurface drainage and lessen waterlogged (Gardner *et al*., 1992).

Season, soil type, timing, tines spacing, shallower leading tines, soil moisture level, and working depth are all variables that must be taken into account because it is not appropriate for all soil types and crops. A meta-analysis of 1530 yield compared at 67 experimental sites to Germany, the United States, Canada, and India revealed increased yield of more than 6% between the deep and ordinary tillage systems (Davies *et al*., 2012). The benefit of combined CTF and SDT could last for three seasons, but it can also last up to ten. The average increase in wheat yield in Western Australia is 0.5 t/ha and 0.6 t/ha at 12 and 16 places respectively.

A comparable technique that involves placing a significant amount of organic matter that has high N levels both below and within the dense clay layers is another option to lessen waterlogging. Sub-soil manuring is the term used to describe this procedure (Celestina *et al.,* 2018). Subsoil restrictions impact over 80% of the farming zone of south eastern Australia that receives medium annually rain fall (375–500 mm) or heavy rainfall (>500 mm). Slotting high amounts (>10 t/ha) of organic matter along with other amendments may help alleviate subsurface restrictions (Armstrong *et al*., 2015). Research conducted in Victoria, Australia showed that by enhancing subsoil structure and providing N, lucerne pellet as well as commercial poultry manure may dramatically increase soil characteristics, crop development, and yield.

Conclusion

An obstacle to maintaining or growing wheat output is the rising severity and frequency of extreme weather such as flooding as a result of global warming. Under waterlogging, the processes of plant development and growth are dependent upon morphological changes, physiological, and biochemical adaptations, as well as the control of genes that affect these characteristics. In order to create more adaptable wheat plants and increase wheat production and grain quality in the face of climate change, it will be important to identify the critical features that underlie tolerance responses and comprehend the roles they play in adaptation to waterlogging. Soil waterlogging has a negative impact on wheat root growth and physiology; the extent of this effect varies based on plant developmental stage, genotype, and environmental factors, particularly soil type and temperature. Certain root response to low O_2, like seminal root survival in brief anoxia, adventitious rooting, quantity of aerenchyma, and lateral root recovery growth after anoxia, are clearly characterized by genotypic diversity. When excessive irrigation is used and ponding of the soil layer lasts more than five days in the start of the wheat blooming cycle, waterlogging damage happens. Wheat farmers will benefit greatly from this research in the future since it will enable them to manage their crops more effectively in the event of prolonged waterlogging.

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